ASSESSING THE WOOD PROPERTIES OF 2-YEAR OLD *EUCALYPTUS TRICARPA*

LISA NGUYEN

School of Forestry, University of Canterbury, New Zealand.

Email: lng28@uclive.ac.nz

Student Number: 43684073

Date of Submission: 18.10.2019

Abstract

This dissertation is focussed on the wood properties of *Eucalyptus tricarpa* at age 2 and their associated genetic parameters. The results of this report are intended to aid the New Zealand Dryland Forests Initiative (NZDFI) project with *E. tricarpa* tree improvement work, with the focus being on the reduction of growth strain.

Six traits for *E. tricarpa* were assessed using 32 families from a breeding trial established in November 2016. The traits were diameter, acoustic velocity (AV), dry density, Modulus of Elasticity (MOE), growth strain and volumetric shrinkage. The genetic parameters analysed were the narrow-sense heritability, genetic correlation and the coefficient of additive genetic variation.

The mean growth strain of *E. tricarpa* was 1735.00 με, which was less than that of three other species of interest in the NZDFI project. The growth strain had a moderate narrow-sense heritability of 0.32, which means that reducing the growth strain via breeding may be a challenge, however, the CV_a for growth strain was 12.32%, meaning that there is scope to manipulate the growth strain.

The genetic correlation between growth strain and MOE was high (0.65), implying a trade-off but this may be offset by the high stiffness wood present in *E. tricarpa*, which had a mean MOE of 11.35 GPa at age 2. The estimated genetic gain showed that the growth strain in *E. tricarpa* could be halved (-52%) if the top family was selected but this would be impractical in a breeding programme. Selection for further tree improvement work should consider selecting multiple families based on their breeding value rankings for growth strain, diameter and MOE.

The main limitation of this study was that the environmental effects on the traits could not be assessed and therefore further studies on *E. tricarpa* wood properties should include multiple sites to analyse these effects.

Acknowledgements

I would like to acknowledge Clemens Altaner, my academic supervisor, for his guidance throughout the research process and for offering me this topic to base my dissertation on in the first place. I would also like to acknowledge Luis Apiolaza for his great support with the statistical analyses involved.

I would also like to thank the students who have helped me with the data collection process over the summer of 2018 and 2019. I would like to thank Ebenezer Iyiola especially, for allowing me access to the ASReml package to complete my analyses, and for weathering my endless questions about tree breeding and quantitative genetics.

Table of Contents

1. Introduction and Background

1.1. New Zealand’s timber resource

Currently, around 90% of New Zealand’s commercial plantation forests consists of *Pinus radiata* and consequently New Zealand’s structural timber market is limited due to the market being dominated by *P. radiata.*

The species generally yields low stiffness timber, with the Modulus of Elasticity (MOE) of 27-year old *P. radiata* ranging from 5.59 – 8.69 GPa (Xu & Walker, 2004). This means that *P. radiata* is able to meet the MOE requirements for lower structural grades such as SG6 or SG8, which are suitable for general framing and flooring joists, and only a small proportion of timber yielded is able to meet the MOE requirements for higher structural grades such as SG10 and SG12 (Grade Right NZ Limited, 2013).

The result is that for engineering design applications which require materials with high stiffness and strength, *P. radiata* timber is a poor competitor against alternative building materials. The current timber products in the market that meet higher structural grades are engineered wood products such as Glulam and laminated veneer lumber (LVL). For example, Nelson Pine Industries’ highest LVL grade offered is LVL13, which has an average MOE of 13.2 GPa (Nelson Pine Industries Limited, 2016). The current structural timber market in New Zealand is limited by the availability of timber that can meet the requirements for the higher structural grades needed to compete with concrete and steel in engineering applications.

P. radiata also produces non-durable timber, which requires preservative treatment such as copper-chromium-arsenic (CCA) for the timber to be used in outdoor applications. Currently, the only disposal methods available for CCA-treated timber is in secure landfills or in highly controlled incineration facilities (Rhodes, 2013). The disposal of CCA-treated timber poses a problem to the environment. In landfills the treated timber leaches copper, chromium and arsenic into the surrounding soil, raising concerns about the contamination of water supplies and waterways (Vogeler et al., 2005). On the other hand, disposal by incineration poses a human health risk to the workers carrying out the disposal. In addition to this, the installation of new of CCA-treated *P. radiata* posts and the use of these posts to replace existing CCA-treated posts in the organic agricultural industry has been banned, which ultimately affects New Zealand’s ability to export organically grown goods. In response, people in the industry have been looking to alternatives to CCA-treated timber posts, including plastic, steel and posts made of naturally durable timber (Millen & Altaner, 2017).

Overall, at present, there is a gap in New Zealand's timber market for high stiffness wood that can meet the requirements for higher structural grades to be used in engineering design applications, and for naturally durable wood that does not require chemical preservative treatment for outdoor applications.

1.2. New Zealand Dryland Forests Initiative

The New Zealand Dryland Forests Initiative (NZDFI) is a project that aims to establish a naturally durable eucalypt resource in the dryland regions of New Zealand. The project was established in 2008 and is a collaborative project involving the University of Canterbury, the Marlborough Research Centre, Proseed, regional councils and landowners from the eastern regions of New Zealand (NZDFI, 2019).

Eucalypts are a promising alternative to *P. radiata* to fill the gap in New Zealand's timber market as eucalypts generally have higher stiffness than *P. radiata* and several species also exhibit natural durability. Under this project, there are five species of interest that have exhibited desirable characteristics such as high natural durability, high stiffness, drought tolerance, frost tolerance and good growth rates in demonstration trials in New Zealand. The five species are: *Eucalyptus bosistoana*, *E. quadrangulata*, *E. globoidea*, *E. tricarpa* and *E. argophloia*.

These species as a result have been selected as the focus for tree improvement work to improve their growth, form and health performance in a New Zealand plantation setting. Tree improvement work for the chosen eucalypt species is also focussed on the reduction of growth strain as it is a severe limiting factor for eucalypt timber processing.

The presence of high growth strain causes defects such as end-splitting and distortion during eucalypt timber processing. Growth strain also causes cracking and splitting in eucalypt veneer, impacting on veneer recovery rates, as shown by a study conducted by Guo & Altaner (2018), which reported that *E. globoidea* veneer recovery varied from 23.6 to 74.5% between trees and was negatively correlated with growth strain. This means that it is important for the NZDFI project to improve traits such as growth, form and health in tree improvement work, but it is also crucial to improve wood properties such as growth strain before an economically viable eucalypt timber resource can be established in New Zealand.

1.3. Tree breeding and eucalypts

In tree breeding, the phenotypic expression of a given trait is considered to be the result of the combination of the genetic and the environmental effects. Tree breeders are interested in manipulating the genetic effects to achieve genetic gain via selective breeding. Genetic gain is the difference between the mean of a trait in the progeny population and the mean of the trait in the parent population. The genetic gain that can be achieved over one breeding cycle is influenced by four factors, which can be described using the Breeder's equation:

$$Genetic\ gain = \frac{Selection\ intensity * \ Selection\ accuracy \ * \ Genetic\ variability}{Time\ to\ deliver\ gain}$$

The genetic gain on a trait increases with increasing selection intensity, increasing accuracy of selection and/or increasing genetic variability of the trait. Gain can also be achieved by decreasing the time it takes for one breeding cycle to turn over. Of these four factors, tree breeders can control the selection intensity and the time to deliver gain in a breeding programme. The selection intensity can be increased by reducing the number of families selected for further breeding from a breeding trial. The time to deliver gain can be decreased carrying out progeny testing and selection process at an early age in a breeding trial.

The accuracy of selection and the genetic variability are two factors which cannot be controlled in a breeding programme but are significant influences on the potential genetic gain that can be achieved. The accuracy of selection can be approximated by the heritability of a trait. If the heritability value is high, the trait is under more genetic rather than environmental control and therefore more gain can be achieved on the trait in a breeding programme. The genetic variability of a trait is also important as it determines the scope of manipulation for a trait of interest. Wild eucalypt populations exhibit great variability (Eldridge et al., 1993), which is advantageous for maximising genetic gain in a breeding programme.

However, in a breeding programme there is usually interest in improving more than one trait concurrently, which means that the correlation between traits of interest must be considered during selection. Phenotypic correlation describes the observed relationship between two traits, which is inclusive of the genetic and environmental effects on the phenotypic expression of the traits. In tree breeding, the genetic correlation between two traits is of more importance, as it describes the response in one trait relative to another trait in response to selection. For example, if the genetic correlation between two traits is positive, the increase in the mean of one trait also results in an increase in the mean of the other trait. Conversely, if the correlation is negative, an increase in the mean of one trait will result in the decrease in the mean of the other trait. If two negatively correlated traits are being selected for, the overall resulting genetic gain from selection is reduced (Eldridge et al., 1993). If two traits have a weak correlation however, an increase in the mean of one trait will have little effect on the mean of the other trait.

One of the key challenges associated with eucalypt tree breeding is that eucalypts can self-pollinate and are prone to inbreeding. This can pose a problem as introduced eucalypts in New Zealand from provenances in Australia could initially exhibit good growth rates, but the quality of the seed produced from these eucalypts may be poor quality due to inbreeding depression. To remediate this problem in the second breeding generation, it is important to source seed from different provenance populations to reduce the relatedness of the genetic material as much as possible, but it may be a challenge if the species has a limited natural range.

1.4. Eucalyptus tricarpa

E. tricarpa, commonly known as ‘red ironbark’, occurs naturally in southern New South Wales in Australia. In its natural range, *E. tricarpa* occurs in open forests growing to 25 – 35 m in height and up to 1 m or more in diameter (Boland et al., 2006). The species has a distinctive deeply furrowed, black bark. The sapwood of *E. tricarpa* is yellow, while the heartwood exhibits a deep red or red-brown colour. The wood is very hard, dense and has a fine texture.

In Australia, the timber is utilised for heavy engineering construction and outdoor applications due to its excellent strength and durability properties, but it is also used for flooring and furniture due to its attractive colour. *E. tricarpa* is one of four species that come under the common name ‘red ironbark’, with the other three species being *E. sideroxylon, E. cebra* and *E. fibrosa* (AgriFutures Australia, 2017). Most, if not all, red ironbark timber in Australia is currently sourced from native forests but there is interest in plantation-grown red ironbark as there is demand for the timber for specialty furniture manufacturing and joinery (AgriFutures Australia, 2017).

E. tricarpa is a species of interest in the NZDFI project for planting into the dryland regions of New Zealand. Drylands are defined as regions which receive 500 – 1000 mm of rainfall per year (Apiolaza et al., 2011). *E. tricarpa* in its natural range is sustained by an average of 550 – 1000 mm of rainfall per year (Boland et al., 2006), which overlaps with the range in the dryland regions. *E. tricarpa* is also known to have high natural durability and stiffness, as summarised by Bootle (2005) who described old-growth *E. tricarpa* as having a Class 1 durability rating and an MOE of 17 GPa. Furthermore, *E. tricarpa* could be well-suited to New Zealand’s temperate climate as it has low to moderate frost tolerance and grows well in temperature ranges of 2 - 28°C (Boland et al., 2006). Under the NZDFI project, the most likely places that *E. tricarpa* would be established are in the drylands and erodible pasture lands of the Canterbury and Marlborough region (Apiolaza et al., 2011; Smethurst, 2011).

If *E. tricarpa* was successfully established in New Zealand as a commercial plantation species, the species may be able to fill the gap for high stiffness timber that can meet high structural grades for engineering applications in the structural timber market. It can also provide a source of naturally durable timber that does not require chemical treatment for outdoor applications, which would be especially beneficial for the organic agricultural industry. Furthermore, having a plantation-grown *E. tricarpa* resource may enable New Zealand access to structural and specialty timber markets overseas.

2. Problem Statement and Research Questions

2.1. Problem Statement

There is little data or information available on the wood properties of plantation-grown *E. tricarpa* and their genetic parameters. To select *E. tricarpa* trees for further tree improvement work, the wood properties of the unimproved trees and their genetic parameters must be known.

The objective of this dissertation is to aid the NZDFI in decision-making on the selection of *E. tricarpa* trees for second-generation breeding work, focussing on the reduction of growth strain, by assessing the wood properties and their associated genetic parameters in a breeding trial.

2.2. Research questions

The research questions intended to be answered in this dissertation report are:

What are the characteristics of the wood properties of *E. tricarpa* at 2 years old?

- Diameter (mm)
- Acoustic velocity (AV) (km/s)
- Dry density (kg/m^3)
- Modulus of Elasticity (MOE) (GPa)
- Growth strain (με)
- Volumetric shrinkage (%)

What are the genetic parameters of these wood properties?

- Narrow-sense heritability (h^2)
- Genetic correlation (r_g)
- Coefficient of additive genetic variation (CV_a)

3. Trial and Data Collection

3.1. NZDFI breeding trial

1384 *E. tricarpa* seedlings were established in the breeding trial by the NZDFI in Murrays Nursery in November 2016. The breeding trial site was located in Woodville, in the North Island of New Zealand.

The half-sibling seedlings established represented 32 open-pollinated families and they were planted in 8-tree family blocks, with each family block being replicated up to 8 times. The family blocks were arranged in a randomised complete block design. A table summarising the families in the trial, the number of replicates per family and the number of trees planted per family can be found in Appendix A.

The trial was harvested in December 2018, where 962 stem samples, approximately 50 cm long, were obtained. These samples were subject to a treatment process to rid them of Paropsine beetles and other insects, before they were delivered to the Wood Technology Laboratory at the University of Canterbury for processing and measurement in the green state. Each sample was labelled to enable identification at the family and tree level, and the samples were also bundled by family block to enable identification and tracking of the replicate number. Sampling, transport and processing was carried out according to NZDFI biosecurity protocols.

3.2. Green measurements

At the Wood Technology Laboratory, the stem samples were debarked to prepare for growth strain and green mass as well as volume measurements.

Growth strain was measured using the splitting test, adapted from Chauhan & Entwistle (2010). The formula used to find the growth strain for each sample was:

$$Growth\ strain = \frac{Opening * \ Diameter}{1.74 * \ Slit\ length^2}$$

The units for growth strain were $\mu\varepsilon$ and the opening, diameter and slit length were measured in mm. The calculation of the growth strain using this splitting test method assumes that growth strain has an equal circumferential distribution within the stem.

The intended slit length was measured and marked on each stem sample and a bandsaw was used to split the stems down to the required slit length (Fig. 1). The diameter of the stem perpendicular to the split plane and the size of the opening created from the split was measured using electronic callipers. For diameter, 1.7 mm was added to the measurements to account for the kerf of the bandsaw.

Figure 1. Two samples split parallel to the stem direction for growth strain measurement.

After the measurements required to determine the growth strain were taken, each stem sample was trimmed to yield two 15 cm half-prongs using a cross-cut saw. The half-prongs were designated ‘side A’ and ‘side B’ to keep track of the individual stem samples (Fig. 2). The mass of the half-prongs was measured using a balance. The volume was measured using the gravimetric water displacement method.

Figure 2. One sample cut into half-prongs, side A and B.

After the green measurements were taken, the half-prongs were oven-dried at 105°C for 48 hours. The samples were then conditioned at a relative humidity of 65% at 25°C until they reached a stable moisture content. The average final moisture content of the samples after conditioning was 8%.

3.3. Dry measurements

The acoustic velocity (AV) of the dried half-prongs were measured using the resonance-based acoustic tool "WoodSpec". The mass of the dried half-prongs was measured using a balance and the volume using the water displacement method.

The dry mass and dry volume measurements of the half-prongs (sides A and B) were used to calculate the dry density of the samples, using the formula:

$$Dry\ density = \frac{Dry\ mass\ A + Dry\ mass\ B}{Dry\ volume\ A + Dry\ volume\ B}$$

The units for dry density were kg/m^3, the units for dry mass for were kg and the units for dry volume were m^3.

The MOE of the samples were calculated from the acoustic velocity (AV) and dry density measurements, using the formula:

$$MOE = Dry\ density * \left(\frac{Acoustic\ velocity\ A + Acoustic\ velocity\ B}{2}\right)^2$$

MOE was given in GPa, the units for dry density were kg/m^3 as stated previously and AV was measured in km/s.

The volumetric shrinkage of the samples was calculated using the green volume and dry volume measurements according to the formula:

$$Volumetric\ shinkage = \left(\frac{(Green\ volume\ A + Green\ volume\ B) - (Dry\ volume\ A + Dry\ volume\ B)}{(Green\ volume\ A + Green\ volume\ B)}\right) * 100$$

The units for volumetric shrinkage were %, while the units for both green and dry volume were m^3.

4. Methods of Analysis

4.1. Characteristics of the wood properties

All data collected was analysed using the R statistical software (R, Version 3.5.2; RCore Team, 2018). Summary statistics were calculated for each of the traits examined for *E. tricarpa* and the phenotypic correlation (*r*) was also found between pairs of traits.

4.2. Genetic parameters

An univariate linear mixed-effects model was used to estimate the genetic parameters of the wood properties, with the model being:

$$y = \mu + replicate + family + \varepsilon$$

Where y is the observed trait, μ is the mean of the trait, replicate refers to the replicate effect on the trait, family refers to the family effect on the trait and ε is the residual error.

The variance components were extracted to calculate the narrow-sense heritability for each trait, with the formula:

$$h^2 = \frac{4 * Var_{family}}{Var_{family} + Var_{replicate} + Var_{residual}}$$

A coefficient of 4 was used to calculate the narrow-sense heritability of the traits because it was assumed that the trees planted were half-siblings. However, eucalypt species are known to be prone to inbreeding so the trees may not be half-siblings, meaning that the heritability values calculated may have the wrong magintude.

The coefficient of additive genetic variability for each trait was calculated using the formula:

$$CV_a = \frac{\sqrt{Var_{family}}}{\mu}$$

The genetic correlation (r_g) between pairs of traits was determined using the ASReml package in R (*v4.1.0.90;* Butler, 2018).

4.3. Genetic gain and breeding values

The potential genetic gain for each individual trait, disregarding correlations between traits, was estimated at different selection intensities. Only 32 families were represented in the breeding trial, so the potential genetic gain was determined for the top 1, 4, 8, and 16 families.

The breeding values of the 32 families for each of the traits examined were calculated and then ranked according to the best to worst breeding values. For diameter, dry density, AV and MOE, the families were ranked from the highest to the lowest breeding values. For growth strain and volumetric shrinkage, the breeding values were ranked from lowest to highest. These rankings were used to identify families that show favourable breeding values, with particular focus on diameter, growth strain and MOE.

5. Results and Discussion

5.1. Summary statistics and phenotypic correlations

The summary statistics for the wood properties of *E. tricarpa* at age 2 are shown in Table 1.

Table 1. Summary statistics of *E. tricarpa* wood properties at age 2.

Trait	Minimum	Mean	Maximum	SD	CV (%)
Diameter (mm)	10.77	23.60	53.60	6.47	27.41
AV (km/s)	3.07	3.80	4.64	0.27	7.19
Dry density (kg/m^3)	658.40	780.30	951.20	44.32	5.08
MOE (GPa)	7.38	11.35	18.58	1.76	15.51
Growth strain (με)	0.00	1735.00	9860.00	757.60	43.67
Volumetric shrinkage (%)	0.60	15.43	26.47	2.97	19.28

The mean MOE of *E. tricarpa* at age 2 was 11.35 GPa (Table 1), which was greater than the MOE of *P. radiata* at the same age, which has been reported to be 2.07 – 3.07 GPa in the green state (Chauhan et al., 2013). *E. tricarpa* also had a stiffness similar to the other eucalypt species of interest in the NZDFI. For example, *E. bosistoana*, the main species of focus in the NZDFI project, was reported to have an MOE of 11.16 GPa at around age 2 (Altaner, 2019). However, it is not as stiff as *E. quadrangulata*, which was 12.86 GPa at age 1.6 years.

The MOE of old-growth *E. tricarpa* in Australia was 17 GPa (Bootle, 2005). This means that at age 2, the mean MOE of *E. tricarpa* grown in the breeding trial was approximately 65% of the MOE of old-growth trees in natural forests. The maximum MOE found in the breeding trial was 18.58 GPa (Table 1), which is greater than the value reported for old-growth *E. tricarpa*. This is favourable as this shows that there is potential to grow *E. tricarpa* trees with improved wood properties in plantations, compared to natural populations, to serve the New Zealand and Australian structural timber markets.

The mean growth strain of *E. tricarpa* was also lower than that of *E. bosistoana* (2072 με), *E. argophloia* (2094 με) and *E. quadragulata* (1784 με) at similar ages (Altaner, 2019). This is favourable as the aim of tree improvement work in the NZDFI is to minimise the growth strain in eucalypts. The CV of growth strain in *E. tricarpa* was 43.67%, which was greater than that of *E. bosistoana* (36.4%), *E. argophloia* (40.9%) and *E. quadrangulata* (26.3%) (Altaner, 2019). This means that there is variation in growth strain in *E. tricarpa* that can be exploited in a breeding programme.

E. tricarpa also had the lowest mean volumetric shrinkage (15.43%) compared to the other species of interest, which ranged from 19.00% to 20.40%. However, *E. tricarpa* reached a mean diameter of 23.60 mm at age 2, which was less than *E. bosistoana* (36.55 mm), *E. argophloia* (35.58 mm) and *E. quadrangulata* (34.78 mm) (Altaner, 2019). This means that *E. tricarpa* exhibits a slower growth rate than these species.

The phenotypic correlations between pairs of traits in *E. tricarpa* at age 2 are shown in Table 2.

Table 2. Phenotypic correlations with 95% confidence intervals in brackets.

Trait	AV	Dry density	MOE	Growth strain	Volumetric shrinkage
Diameter	0.02 (-0.04, 0.08)	0.11 (0.05, 0.17)	0.05 (-0.01, 0.18)	0.13 (0.07, 0.19)	0.01 (-0.06, 0.07)
AV		0.00 (-0.06, 0.07)	0.93 (0.92, 0.94)	0.24 (0.18, 0.30)	0.01 (-0.05, 0.08)
Dry density			0.37 (0.31, 0.42)	0.01 (-0.05, 0.08)	0.42 (0.37, 0.47)
MOE				0.23 (0.17, 0.29)	0.17 (0.11, 0.23)
Growth strain					0.10 (0.03, 0.16)

The traits of *E. tricarpa* had a weak to moderate positive relationship with each other, except for AV and MOE, which had a strong positive relationship (0.93) (Table 2). The phenotypic correlations between traits is of little importance from the perspective of a tree breeder as they only indicate the relationship between the performance of two traits.

The information may be used to predict the performance of one trait by measuring another as wood properties often cannot be easily measured. However, the relationships between the traits in *E. tricarpa* were weak to moderate, making this approach inefficient.

5.2. Heritability and genetic correlations

The narrow-sense heritability and the coefficient of additive genetic variation were calculated for the wood properties of *E. tricarpa* and are shown in Table 3.

Table 3. Narrow-sense heritability (h^2) with 95% confidence intervals in brackets, and coefficient of additive genetic variation (CV_a).

Trait	h^2	**CV_a (%)**
Diameter	0.75 (0.65, 0.87)	11.80
AV	0.75 (0.37, 1.00)	3.17
Dry density	0.70 (0.34, 1.00)	2.36
MOE	0.63 (0.25, 0.94)	6.24
Growth strain	0.32 (0.10, 0.51)	12.32
Volumetric shrinkage	0.30 (0.10, 0.51)	5.30

The heritability of most of the wood properties for *E. tricarpa* were high, except for growth strain and volumetric shrinkage, which had moderate heritability values (Table 3). This shows that the wood properties of *E. tricarpa* could be easily improved in a breeding programme via selection, but it may be more difficult to improve growth strain and volumetric shrinkage as it appears that these traits were under more environmental control.

However, growth strain had the highest CV_a value, which shows that the trait had great genetic variability. There is a greater scope to manipulate the growth strain in a breeding programme compared to the other traits, which is favourable as growth strain is the principal trait of interest for improvement. Diameter also had a high CV_a value (11.80%), which means that it also has a great scope for manipulation in a breeding programme. This high CV_a value, combined with the high heritability of diameter (0.75) shows that the growth rate of *E. tricarpa* could be improved easily via selective breeding.

The calculated heritability values (Table 3) were most likely overestimated as the calculations were based on the assumption that the trees in the trial were half-siblings. In reality, this may not be true as the relatedness of the families established for *E. tricarpa* in the breeding trial is unknown.

The relatedness coefficient for trees that are pure half-siblings are 0.25, assuming that the parent trees are not related or inbred. This means a coefficient of 4 is assumed to be appropriate to calculate the narrow-sense heritability. However, the assumption of pure half-siblings is rarely true, especially for eucalypts which are prone to self-pollination and inbreeding, and therefore the actual relatedness coefficient is likely greater than 0.25 (Squillace, 1974). This results in an overestimation of the heritability values.

The heritability values for the wood properties of *E. tricarpa* were compared to the heritability values reported for *E. bosistoana* and *E. quadrangulata*, at ages 2 and 1.6 years respectively (Table 4).

Table 4. Narrow-sense heritability (h^2) with 95% confidence intervals in brackets, for *E. bosistoana* and *E. quadrangulata*.

Trait	***E. bosistoana*** **(Davies, Apiolaza, & Sharma, 2017)**	***E. quadrangulata*** **(Altaner, 2019)**
Diameter	0.76	0.20
	(0.42, 1.00)	(0.10, 0.31)
AV	0.97	0.67
	(0.60, 1.00)	(0.46, 0.85)
Dry density	-	0.37
		(0.18, 0.54)
MOE	0.82	0.79
	(0.48, 1.00)	(0.53, 1.00)
Growth strain	0.63	0.40
	(0.28, 0.98)	(0.26, 0.56)
Volumetric shrinkage	0.29	0.92
	(0.13, 0.45)	(0.59, 1.00)

The heritability of the wood properties for *E. tricarpa* were similar to those reported for *E. bosistoana* at age 2, except for growth strain where the value for *E. bosistoana* is higher (0.63). The growth strain heritability value in *E. tricarpa* (0.32) was more similar to that of *E. quadranguata* (0.40).

The 95% confidence intervals for the heritability of growth strain across all three species overlap, which could mean the differences in heritability for growth strain between the species were not significant. However, this overlap may be due to greater uncertainty in the calculation of heritability. 83 families were assessed to calculate the heritability values for *E. quadrangulata* (Altaner, 2019) while 40 families were assessed for *E. bosistoana* (Davies, Apiolaza, & Sharma, 2017) and 32 families were assessed for *E. tricarpa*. As fewer families were assessed for *E. bosistoana* and *E. tricarpa* compared to *E. quadrangulata*, the heritability values calculated for these two species were likely less precise than those calculated for *E. quadrangulata*, resulting in larger 95% confidence intervals.

The genetic correlations between pairs of traits were determined for *E. tricarpa* at age 2 and are displayed in Table 5.

Table 5. Genetic correlations with 95% confidence intervals in brackets.

Trait	**AV**	**Dry density**	**MOE**	**Growth strain**	**Volumetric shrinkage**
Diameter	-0.20 (-0.64, 0.21)	0.64 (0.34, 0.89)	0.04 (-0.39, 0.45)	-0.33 (-0.73, 0.10)	-0.22 (-0.66, 0.25)
AV		-0.12 (-0.56, 0.32)	0.93 (0.88, 0.99)	0.72 (0.44, 0.99)	-0.09 (-0.56, 0.39)
Dry density			0.25 (-0.17, 0.65)	-0.19 (-0.61, 0.28)	0.21 (-0.24, 0.64)
MOE				0.65 (0.32, 0.96)	0.00 (-0.47, 0.45)
Growth strain					-0.17 (-0.70, 0.39)

The genetic correlation between traits is of more relevance to tree breeders as it indicates the response of one trait to the selection of another trait. The direction and strength of the genetic correlations between traits has implications on the trade-offs that may occur and the effect on the overall genetic gain from selection.

The correlation between growth strain and MOE was moderately high (0.65) (Table 5). This implies that when selecting and breeding to reduce growth strain in *E. tricarpa*, MOE will be reduced concurrently, resulting in a trade-off between the traits. A reduction in the MOE associated with a reduction in growth strain might be acceptable, as *E. tricarpa* has high stiffness wood at a young age (Table 1). The reduction in MOE may not have a significant impact on the ability of *E. tricarpa* timber to meet higher structural grade requirements, but a reduction in growth strain could greatly improve the recovery rates in the processing of the timber.

Diameter and growth strain were negatively correlated (-0.33), which implies that selection for a reduction in growth strain will result in a moderate increase in diameter. This is favourable as this means that the growth rates of *E. tricarpa* can be improved while reducing the growth strain in the species.

5.3. Estimated genetic gain for *E. tricarpa* and family breeding value rankings

Estimated genetic gains for individual traits, disregarding the genetic correlations between the traits, were calculated (Table 6). Only 32 families were represented in the breeding trial, so the genetic gain was estimated for the top 1, 4, 8, and 16 families.

Table 6. Estimated genetic gain for individual traits of *E. tricarpa*, with gain as a percentage of the mean in brackets.

Trait	Mean	Top 1	Top 4	Top 8	Top 16
Diameter (mm)	23.60	11.34 (48%)	7.92 (34%)	6.12 (26%)	3.98 (17%)
AV (km/s)	3.80	0.43 (11%)	0.31 (8%)	0.24 (6%)	0.16 (4%)
Dry density (kg/m^3)	780.30	72.80 (9%)	52.33 (7%)	39.63 (5%)	25.31 (3%)
MOE (GPa)	11.35	2.05 (18%)	1.60 (14%)	1.32 (12%)	0.94 (8%)
Growth strain (με)	1735.00	-910.64 (-52%)	-611.90 (-35%)	-407.09 (-23%)	-241.94 (-14%)
Volumetric shrinkage (%)	15.43	-4.30 (-28%)	-2.38 (-15%)	-1.53 (-10%)	-0.87 (-6%)

Growth strain in *E. tricarpa* via selection of families could be reduced by up to 52% if the top family was selected (Table 6). However, selecting only the top family would be impractical as this would severely reduce the genetic variation in the selected population, limiting the opportunity for further breeding work. Similarly, the gain on diameter can be up to 48% if the top family were selected but this is also an impractical option in a breeding programme, given the limited number of families. A modest reduction in growth strain (-14%), however, could be achieved if the top 16 families, or the top 50%, from the trial were selected for further breeding.

The values for the estimated genetic gain on the traits do not take the genetic correlations of the traits into account, therefore the overall genetic gain that can be achieved if multiple traits were being selected concurrently will be less. This is important considering that there will be a trade-off between MOE and growth strain when reducing the growth strain in *E. tricarpa* via selection. This means that the actual gain achieved from selection will likely be less than the estimated genetic gain values because there must be an acceptable limit on how much of a reduction in MOE can be tolerated for a reduction in growth strain, thereby limiting the gain which can be achieved on growth strain.

The breeding values for each family represented in the trial were calculated and the families were ranked from best to worst (1st to 32nd) for diameter, growth strain and MOE based on these breeding values (Fig. 3). The breeding value was calculated as the deviation of the family mean from the overall mean of the trait. For diameter and MOE, breeding values were ranked from positive to negative as increases in diameter and MOE are desirable. For growth strain, the breeding values were ranked inversely, from negative to positive, as a reduction in growth strain is desirable.

The family breeding values for all traits can be found in Appendix B and the corresponding family rankings for all traits can be found in Appendix C.

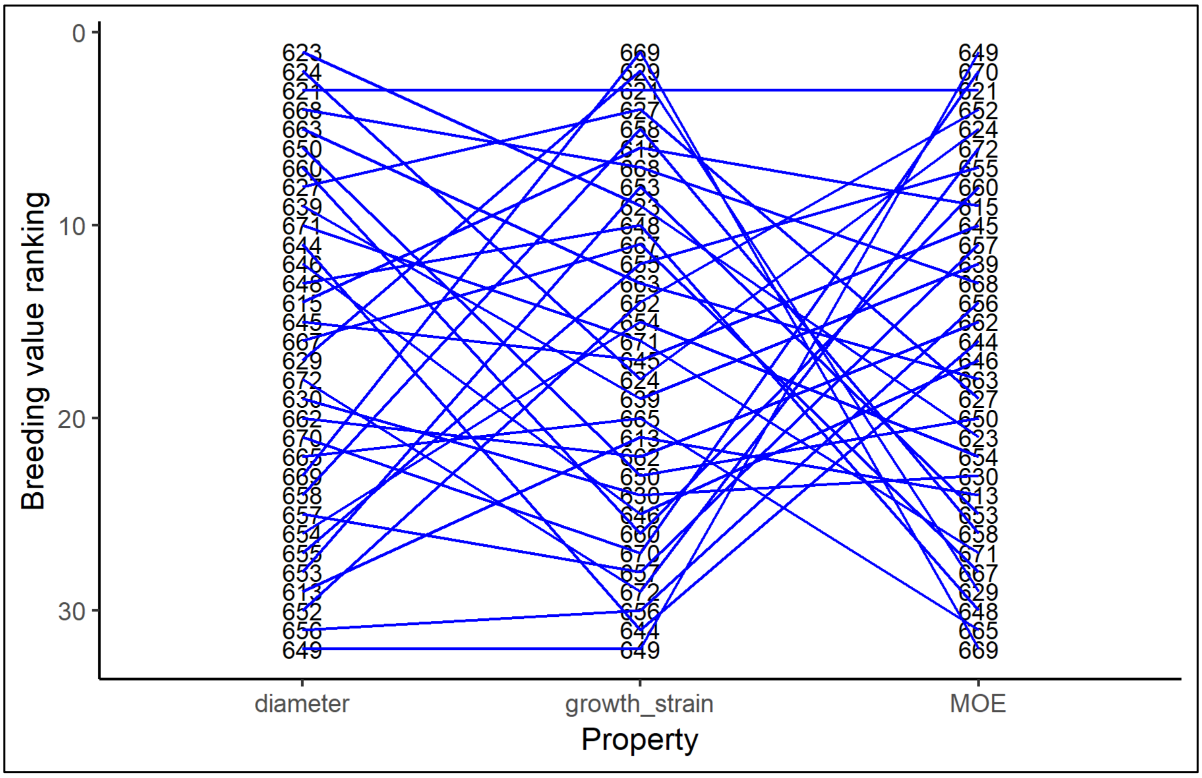

Figure 3. Family breeding value rankings for diameter, growth strain and MOE.

The breeding value rankings for each family varied between the traits. Family 621 consistently ranked 3rd for diameter, growth strain and MOE. This means that Family 621 is the most promising family for the improvement of *E. tricarpa*, however, as stated above, selecting one family is impractical.

Instead, multiple families should be selected for further tree improvement work to maintain high genetic variation, though this will be at the cost of genetic gain. A possible method to select families for further breeding work, based on their breeding values for diameter, growth strain and MOE is shown in Figure 4.

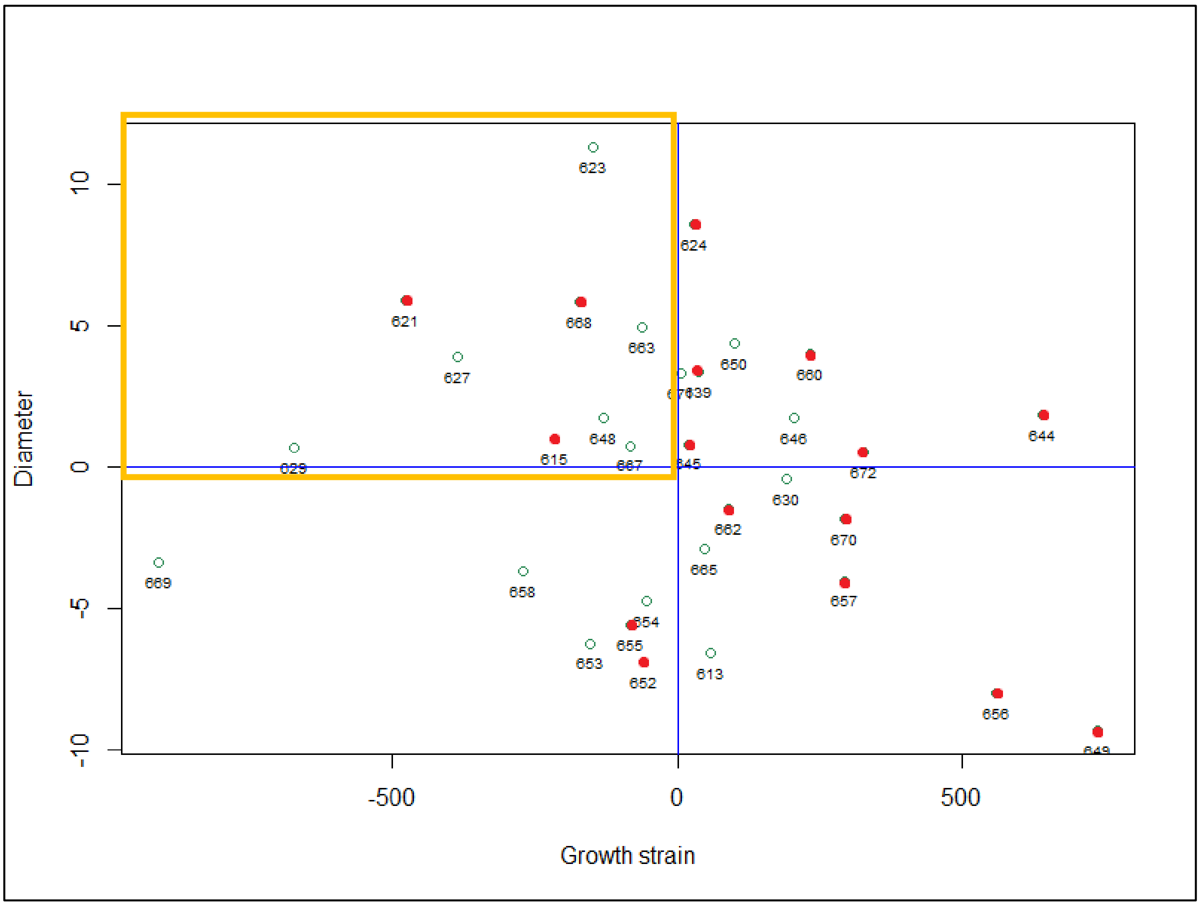

Figure 4. Family breeding values for growth strain vs. diameter, with top 16 families for MOE marked with red circles.

If selection were to be based on diameter and growth strain, then families with lower than average growth strain and higher than average diameter, found in the yellow highlighted top-left quadrant (Fig. 4) may be selected. 9 families meet these criteria. If MOE were taken into consideration, however, selection would be narrowed down to 3 families as only 3 families have above average diameter, growth strain and MOE, highlighted by the red circles in the top-left quadrant.

6. Conclusions and Recommendations

E. tricarpa has promising wood properties compared to *P. radiata* and the other eucalypt species of interest, especially in terms of MOE, growth strain and volumetric shrinkage. This means that *E. tricarpa* could be well-suited to filling the gap in the New Zealand structural timber market for high stiffness wood for engineering design applications. However, the growth rate of *E. tricarpa* is relatively slow compared to the other species of interest. This means that tree improvement work done on *E. tricarpa* may have to focus on improving the growth rate in addition to reducing the growth strain in the species.

The narrow-sense heritability of growth strain was moderate (0.32), which means that reducing the growth strain via breeding may be challenging as it seems that the trait was more under environmental control. However, the CV_a for growth strain was 12.32%, meaning that there is scope to manipulate growth strain. Diameter had a high heritability value (0.75) and a large CV_a (11.80%), meaning that there is potential to improve the growth rate of *E. tricarpa*.

The genetic correlation between growth strain and MOE was high (0.65), implying a trade-off between the two traits but this may be offset by the fact that *E. tricarpa* had high stiffness wood. The negative genetic correlation between growth strain and diameter (-0.33) is favourable as it means the growth rate of *E. tricarpa* could be improved while the growth strain is reduced. Overall, the benefit of reducing the growth strain and increasing the growth rate in *E. tricarpa* might outweigh the disbenefit of reducing MOE.

The estimated genetic gain for individual traits showed that the growth strain in *E. tricarpa* could potentially be halved if the top family was selected but this is impractical as the genetic variation in the selected population would be severely reduced. Similarly, though Family 621 was favourable in terms of its breeding value ranking for diameter, growth strain and MOE, family selection for further tree improvement work should include more than one family to maintain broad genetic variation. Selection for further tree improvement work should consider selecting multiple families based on their breeding value rankings for growth strain, diameter and MOE. A possible method of selection was shown in Figure 4, where 9 families met the criteria for above-average growth strain and diameter while 3 families had above-average MOE in addition to this.

Overall, the selection of families is a complex decision, which involves the consideration of the desired outcome of breeding against the potential trade-offs. Reducing the growth strain in eucalypts is critical to improve the processing of eucalypt timber, however, selection to solely maximise the gain on growth strain in *E. tricarpa* will result in a reduction in the MOE and the genetic variation of the selected population. The families that are selected will also ultimately depend on the weighting of the traits of interest which will depend on the economic importance of the traits, which is currently unknown.

The main limitation of this study was that genetic effects and environmental effects on the observed wood properties could not be partitioned as only one breeding trial site was examined. In addition to this, the breeding trial was established at a nursery site, which has uniform and favourable growing conditions, which are not representative of potential plantation sites for *E. tricarpa*. This means that the values for the wood properties presented in this dissertation will not necessarily reflect the species' performance on a plantation site.

Another limitation was that only 32 families were assessed in this dissertation to estimate the genetic parameters for the traits of *E. tricarpa*. This means that the values calculated for the genetic parameters most likely have a large degree of uncertainty associated due to sampling error. The NZDFI has a target size of 100 families per breeding population but this target has not been reached yet as seed collection has been limited by poor flowering years (NZDFI, 2017).

It is recommended that further studies on the wood properties of *E. tricarpa* under the NZDFI project should incorporate multiple sites to partition the genetic and environmental effects on the wood properties, as well as examine if there are any interaction effects between genetics and the environment. It is also recommended that further studies should examine a larger number of families, ideally the target number of 100 families as intended by the NZDFI, to reduce the uncertainty of genetic parameter calculations for *E. tricarpa*.

References

AgriFutures Australia. (2017). Red ironbark. Retrieved from: https://www.agrifutures.com.au/farm-diversity/red-ironbark/

Altaner, C. (2019). *Minimising growth-strain in eucalypts to transform processing*. Wellington, New Zealand: Ministry of Primary Industries.

Apiolaza, L. A., McConnochie, R., Millen, P., Van Ballekom, S., & Walker, J. C. F. (2011). Introducing durable species to New Zealand drylands: genetics of early adaptation of *Eucalyptus bosistoana*. In *Developing a Eucalypt Resource: Learning from Australia and elsewhere*. (pp. 137-146). Christchurch, New Zealand: Wood Technology Research Centre.

Boland, D. J., Brooker, M. I. H., Chippendale, G. M., Hall, N., Hyland, B. P. M., Johnson, R. D., Kleinig, D. A., McDonald, M. W., & Turner, J. D. (2006). *Forest trees of Australia* (5th ed.). Melbourne, Australia: CSIRO Publishing.

Bootle, K. R. (2005). *Wood in Australia: types, properties, and uses* (2^{nd} ed.). Sydney, Australia: McGraw-Hill.

Butler, D. (2018). ASReml: Fits the Linear Mixed Model. R package version 4.1.0.90. https://asreml.org

Chauhan, S., & Entwistle, K. (2010). Measurement of surface growth stress in *Eucalyptus nitens* Maiden by splitting a log along its axis. *Holzforschung*, *64*, 267- 272. https://doi.org/10.1515/HF.2010.022

Chauhan, S. S., Sharma, M., Thomas, J., Apiolaza, L. A., Collings, D. A., & Walker, J. C. F. (2013). Methods of the very early selection of *Pinus radiata* D. Don. for solid wood products. *Annals of Forest Science*, *70*, 439- 449. https://doi.org/10.1007/s13595-013-0270-3

Davies, N. T., Apiolaza, L.A., & Sharma, M. (2017). Heritability of growth strain in *Eucalyptus bosistoana*: a Bayesian approach with left-censored data. *New Zealand Journal of Forestry Science*, *47(5)*. https://doi.org/10.1186/s40490-017-0086-2

Eldridge, K., Davidson, J., Harwood, J., & Van Wyk, G. (1993). *Eucalypt domestication and breeding*. New York, United States: Oxford University Press Inc.

Grade Right NZ Limited. (2013). Grade verified information sheet. Retrieved from: https://www.graderight.co.nz/downloads/Grade_Verified_Info_Sheet.pdf

Guo, F., & Altaner, C. M. (2018). Properties of rotary peeled veneer and laminated veneer lumber (LVL) from New Zealand grown *Eucalyptus globoidea*. *New Zealand Journal of Forestry Science. 48*(3). https://doi.org/10.1186/s40490-018-0109-7

Millen, P., & Altaner, C. (2017). *Performance of naturally durable eucalypt posts in Marlborough vineyards*. (Publication No.: SWP-T039). Retrieved from: http://nzdfi.org.nz/wp-content/uploads/2017/11/SWP-T039-DurableEucalyptVineyardPost-171026-final.pdf

Nelson Pine Industries Limited. (2016). NelsonPine LVL specific engineering design guide. Retrieved from: http://www.nelsonpine.co.nz/wp-content/uploads/LVL_Specific_Engineering_Design_Guide.pdf

New Zealand Dryland Forests Initiative. (2017). NZDFI breeding research plan. Retrieved from: http://nzdfi.org.nz/wp-content/uploads/2017/03/Section-1-NZDFI-Breeding-Research-Plan.pdf

New Zealand Dryland Forests Initiative. (2019). New Zealand Dryland Forests Initiative: breeding tomorrow's trees today. Retrieved from: https://nzdfi.org.nz/

R Core Team. (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rhodes, S. (2013). Recovery and disposal options for treated timber. Retrieved from: https://www.wasteminz.org.nz/wp-content/uploads/Scott-Rhodes.pdf

Smethurst, P. (2011). Genotype-site matching and managing for abiotic constraints: dryland eucalypts for the South Island. In *Developing a Eucalypt Resource: Learning from Australia and elsewhere*. (pp. 93-104). Christchurch, New Zealand: Wood Technology Research Centre.

Squillace, A. E. (1974). Average genetic correlation among offspring from open-pollinated forest trees. *Silvae Genetica, 23(5),* 149-156.

Vogeler, I., Green, S., Greven, M., Robinson, B., van den Dijssel, C., & Clothier, B. (2005). *Environmental risk assessment of CCA leaching from treated vineyard posts*. Retrieved from: https://www.marlborough.govt.nz/repository/libraries/id:1w1mps0ir17q9sgxanf9/hierarchy/Documents/Environment/Groundwater/Groundwater%20Reports%202005%20List/Environmental_Effects_of_CCA_Treated_Posts_Stage_2_Report_October_2005.pdf

Xu, P., & Walker, J. C. F. (2004). Stiffness gradients in radiata pine trees. *Wood Science and Technology, 38(1),* 1-9. https://doi.org/10.1007/s00226-003-0188-2

Appendices

Appendix A. Summary of *E. tricarpa* families established in the breeding trial.

Family code	Number of replicates	Number of trees planted	Numbers of trees sampled
613	1	8	3
615	1	8	7
621	5	40	29
623	8	64	48
624	8	64	53
627	3	24	12
629	4	32	26
630	1	8	4
639	8	64	55
644	8	64	48
645	2	16	7
646	8	64	53
648	2	16	10
649	8	64	34
650	8	64	57
652	8	64	37
653	8	64	21
654	8	64	48
655	8	64	43
656	8	64	42
657	8	64	45
658	8	64	48
660	3	24	20
662	3	24	15
663	3	24	20
665	8	64	37
667	1	8	5
668	1	8	5
669	8	64	40
670	6	48	38
671	8	64	46
672	1	8	6
	Total	**1384**	**962**

Appendix B. Family breeding values for all traits.

Family code	Diameter (mm)	AV (km/s)	Dry density (kg/m^3)
613	-6.56	-0.12	-16.09
615	1.00	0.09	10.16
621	5.91	0.17	27.97
623	11.34	0.00	4.21
624	8.58	0.08	50.55
627	3.92	-0.03	20.95
629	0.68	-0.44	41.73
630	-0.42	-0.06	6.86
639	3.39	0.02	35.84
644	1.85	0.02	14.07
645	0.83	0.08	11.18
646	1.75	0.02	10.57
648	1.74	-0.39	-3.03
649	-9.29	0.43	-29.10
650	4.37	-0.02	17.23
652	-6.89	0.34	-49.74
653	-6.22	-0.08	-27.92
654	-4.71	0.08	-34.18
655	-5.57	0.24	-20.23
656	-7.98	0.15	-19.60
657	-4.01	0.20	-25.95
658	-3.65	-0.07	-38.60
660	4.03	0.19	-13.12
662	-1.46	0.04	11.69
663	4.97	0.06	-14.52
665	-2.90	-0.25	-92.75
667	0.78	-0.26	-19.70
668	5.84	0.00	44.23
669	-3.37	-0.53	6.13
670	-1.82	0.11	72.80
671	3.34	-0.27	22.98
672	0.54	0.22	-4.61

Appendix B. Family breeding values for all traits cont.

Family code	MOE (GPa)	Growth strain (με)	Volumetric shrinkage (%)
613	-0.76	57.90	-0.09
615	0.70	-215.20	-0.53
621	1.41	-476.87	0.22
623	-0.10	-149.15	-1.75
624	1.12	28.80	1.84
627	0.09	-385.50	-1.76
629	-1.95	-674.60	0.59
630	-0.17	192.67	0.28
639	0.56	36.66	-0.21
644	0.29	642.44	-0.46
645	0.70	19.70	0.12
646	0.21	205.89	-0.18
648	-2.13	-130.62	0.28
649	2.05	738.36	0.18
650	0.06	101.19	-0.19
652	1.20	-58.41	-0.64
653	-0.91	-152.66	-0.48
654	-0.11	-54.44	1.49
655	0.99	-82.10	0.22
656	0.55	559.89	1.86
657	0.69	295.08	1.83
658	-1.00	-270.25	0.69
660	0.95	233.34	-0.50
662	0.39	89.76	-1.72
663	0.19	-62.33	-1.03
665	-2.69	48.10	-4.30
667	-1.60	-83.88	0.82
668	0.56	-171.00	0.15
669	-2.83	-910.64	2.67
670	1.72	292.58	-0.17
671	-1.30	6.56	0.75
672	1.11	328.74	0.01

Appendix C. Family breeding value rankings for all traits.